Heat Flux Sensor Development for GE Appliances (Smart Cookie)

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Distinction in the Department of Mechanical Engineering at The Ohio State University

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Abstract

GE Appliances strives to design an oven that bakes every type of food exactly to the consumer's liking every time. This objective can be achieved by mapping the input parameters of the oven design that can be controlled- such as heating element placement, temperature, and cycle time- to output variables by which the consumer knowingly or unknowingly judges the bake quality - such as the food's crispiness, color, and the evenness of the bake. Both the convective and radiative heat flux inside the oven directly affect the bake quality, however GE Appliances does not currently have an effective and affordable way to measure these two variables. The purpose of this research is to develop a prototype heat flux sensor that GE Appliances can easily manufacture and use throughout their testing facility to measure the convective and radiative heat flux. The data collection and analysis methods have previously been simulated and verified by former graduate student Suraj Kant. He also created a first-generation prototype and established general parameters for the heat flux sensor design. A second-generation prototype will be created from this baseline to improve several aspects of the design. First, specific improvements to the first generation's pin polishing methods, insulation, and body shape will be developed in order to increase accuracy and durability. The second-generation design will then incorporate these specific improvements along with wireless data collection, a self-contained cooling system, and better manufacturability and ease of maintenance for long term use. The overall goal of this phase of work is the development of a durable and easy to use heat flux sensor that can record heat flux values at a sampling rate of at least 1Hz from within an oven for a period of one-half hour at 450 °F. This heat flux sensor will enable GE Appliances to record convective and radiative heat flux inside their test ovens to better understand the effect of varying numerous oven parameters. This will eventually enable the

creation of an accurate model of the oven, shortening the calibration and testing phases by enabling the oven designers to understand the relationships between parameters before a new oven is ever built.

Acknowledgements

I would like to first thank my advisor Dr. Sandra Metzler for her abundance of support, guidance, and encouragement that she has provided throughout this project. She helped me to find a passion for knowledge that I didn't know I had and, as a result, I am more confident and excited for my future than ever before. Her professional knowledge and intelligence in the mechanical field were vital in the creation of this thesis. There is not enough room on the page to express the real impact she has had on my life and I am blessed to have her as my mentor and role model.

I would also like to thank Dr. Zhenyu Wang and Dr. Shawn Midlam-Mohler for supporting me by being liaisons with the GE Appliances team and helping to strengthen the corporate-academic partnership which allowed this project to take place. Thank you to Sabrina Hannah and James Armstrong from GE Appliances for your support and patience: your input and guidance helped me continue to progress over the past year. I would also like to thank Nicholas Okruch from the GE Prototype lab for his extremely helpful input on the design and construction of the sensor body. Without his resources and knowledge of manufacturing processes the final sensor could not have withstood the heat of the oven. Thank you to Dylan DeSantis for sharing his expertise in all things electronics related and for helping me select the correct components in my circuitry.

Finally, I would like to thank my parents for their support and love throughout my schooling and especially in my final semester. Their continued enthusiasm for my knowledge provided me with an important foundation that I will carry with me forever. They provided me with a wonderful education at Ohio State and have shown me that I can do anything I put my mind to.

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Chapter 1: Introduction

GE Appliances designs and manufactures a variety of appliances in their Louisville plant, one of these being their residential oven. The oven has a large number of design parameters that vary between models such as the heating element geometry, materials, rack placement, air flow characteristics, and many more. These numerous design variables make it difficult to map the changes made to the design between oven models to the desired outcome: perfectly cooked food. The GE Appliances oven testing lab in Louisville, KY currently performs their testing of each oven model by baking various foods – cookies, cakes, pot roast, turkey – and measuring the quantifiable variables. To use the cookie as an example, the dough recipe, spacing on the tray, and cooking times are held constant while the control system varies the oven cycles slightly. The final height, shape, and color, and position are recorded for every cookie on the pan and this data is used to calibrate and verify the final oven model design.

While the GE Appliances testing lab has perfected this process of measuring these dependent variables, it is desirable to create a testing process that can map the oven environment parameters to the outcomes concerning food without the need to constantly bake various foods in the lab. The reduction of material costs (in baking equipment and ingredients) and the elimination of the employee time cost associated with these tests would be very beneficial to the company. GE Appliances has already identified the convective and radiative heat flux through the food to be a reliable variable that fits this need. The heat flux through each type of food can be used to accurately predict how that food will cook. With an accurate and repeatable method to measure these two types of heat transfer inside the oven environment, the brute force method of testing can be eliminated and replaced with a digital and more repeatable process that saves GE Appliances money and time throughout the oven design process.

1.1 Focus of Thesis

The purpose of this work was to design, construct, and validate a heat flux sensor for use in the GE Appliances oven testing facilities. Phase one of this project was completed by Suraj Kant, and this work was published in his master's thesis in Spring 2018. In phase two, the initial heat-flux sensor prototype concept is improved upon using heat transfer basics, the incorporation of integrated electronics, and the engineering design process to create a cost-effective sensor that can collect accurate and repeatable data. Both radiative and convective heat flux can be measured using this device.

1.2 Significance of Research

Heat flux though an object is an important variable in many applications. There are a few commonly known methods to measure the flow of heat through a material, all of which use the basic concept of energy balance in a system. Heat flux cannot be determined exactly at every point in a system, but it can be approximated using an integral over the whole system.

By building a custom sensor utilizing this same principle, we can measure the convective and radiative heat flux at a given area inside the oven's environment. There are no simple heat flux sensors on the market that can provide the data that GE Appliances needs for their testing lab. This custom sensor will allow the oven testing lab to easily and accurately measure the heat flux inside their ovens, ultimately shortening the oven calibration time and allowing the engineers there to develop a wider range of modes with specific cook times and temperatures for each type of food.

1.3 Overview of Thesis

This thesis has 5 chapters. Chapter 2 discusses previous work done in the first phase of this project, including the proof of concept for the initial sensor design and the first sensor prototype.

Chapter 3 discusses the design process methodology surrounding the phase two sensor body, including material choices and the body shape redesign. Chapter 4 discusses the design process used to create the custom data processing circuit to maximize accuracy and repeatability within sensors. This chapter also includes a description of the python code for the sensor's microcontroller. Chapter 5 discusses the overall user interface of the heat flux sensing system. Again, the design process is used to generate ideas and prototype. Chapter 6 contains the results of the functionality testing and final sensor cost, and Chapter 7 contains the discussion. Finally, Chapter 8 summarizes the deliverables of this project and discusses future directions of study.

Chapter 2: Previous Work (Phase 1)

Suraj Kant Sahu completed his master's thesis on the first phase of this project. It is important to understand his work in developing the concept, creating a model, simulating it, validating basic design choices, and producing a basic prototype. My part in this research builds directly from his work and initial prototype. The working principle is explained in detail below in section 2.1 to provide a foundation of the heat transfer principles used inside the sensor. This project will use the same design requirements as those set out for phase 1, and these are reiterated in section 2.2. Finally, the initial prototype created in phase 1 is outlined in section 2.3 as a baseline for the design improvements made throughout this project.

2.1 Working Principle

It is important to understand the relationship between the parameters that can be controlled inside the oven design – temperature, heating element placement, cycle time, etc. – and the output variables that manifest in the way food is cooked – lightness, color, surface temperature. It has been observed that when the oven temperature is set to a constant, the mode of heat transfer to the food itself can still significantly vary these resulting output variables [1]. This study introduced the importance of the measurement of heat flux to the oven design industry and is a catalyst for this research project.

It is a known principle of heat transfer that a body placed inside a heated oven will absorb both radiative and convective heat flux. An object with a high emissivity coefficient (close to 1) will experience significant heat transfer effects from both types of heat flux from the system, while an object with a low emissivity constant (close to 0) will only experience significant convective heat flux. This differential behavior related to the emissivity of an object can be utilized to develop two types of sensors, one that primarily measures convection and a second that measures both convection and radiation. Labeling these bodies, A for high emissivity and B for low emissivity, the heat flow equations for both bodies can be formulated as shown below [1]. By utilizing the simple shell equations outlined below, each mode of heat flux entering these bodies can be measured.

$$\dot{Q}_A = \varepsilon_A \dot{Q}_{rad,bb} + \dot{Q}_{conv}$$
$$\dot{Q}_B = \varepsilon_B \dot{Q}_{rad,bb} + \dot{Q}_{conv}$$

where,

$\dot{Q}_A =$ total heat flux measured by high-e sensor

$\dot{Q}_B =$ total heat flux measured by low-e sensor

$\varepsilon_A =$ emisivity of high-e sensor

$\varepsilon_B =$ emisivity of low-e sensor

$\dot{Q}_A \; measures \; total \; heat \; flux$

$\dot{Q}_B \; measures \; mostly \; convective \; heat \; flux$

A thermal gradient can be generated across the sensor pins by cooling one end relative to the other, to ensure heat flow through the bodies. Heat flux can then be calculated using the temperature differential across the pin body, utilizing thermocouples to measure temperature at both the top and bottom surfaces of the high and low emissivity bodies. The conservation of energy and assumption of isolation around the two bodies allows the radiative heat flow to be calculated by subtracting the heat flow through body A from the heat flow through body B. A diagram of this process is shown in Figure 1.

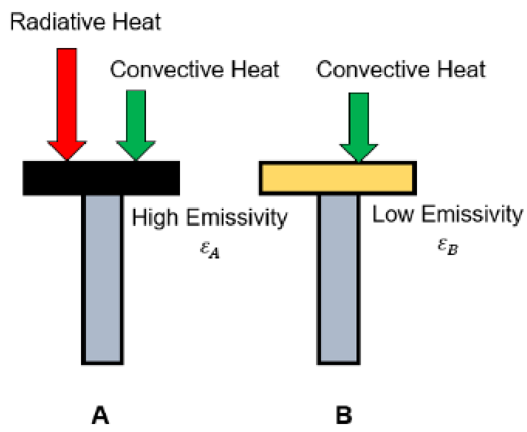


Figure 1: Heat Flux Working Principle

2.2 Sensor Design Requirements

The key overall design requirements remain the same as phase 1 and are listed below. These were agreed upon by the GE Appliances team and are also contained in the project proposal [2].

- The device will be able to measure radiant and convective heat transfer with a +/- 10% accuracy
- The device will be able to measure radiant and convective heat transfer with a repeatability less than 2% (determined using coefficient of variance)
- The device will be able to endure oven temperatures for the duration of a preheat cycle and 30 minutes of steady-state cooking at 450 F°
- The device will be able to measure convective and radiative heat flux from the top surface
- The target cost for device is less than $1,000
- Minimally disruptive to the oven environment (minimal cords, cooling supplies, etc.)
- The size of the device should be no larger than 3” x 3” x 1”

2.3 Phase 1 Sensor Prototype Results

The Phase 1 prototype was able to successfully recreate the data obtained by the existing heat flux sensor (RC01) for both high emissivity and low emissivity heat flux values at a fraction of the cost of the currently available commercial system [1]. A DAQ system consisting of a 4 National Instruments (NI) modules (NI-9214 received the thermocouple signals through a 16-channel input TB-9214, the module was connected to controller NI-9024 via NI-CRio chassis NI-9211) collected the thermocouple data and transmitted it from the controller to the system via an ethernet cable. The prototype body included two sensor pins that were turned on a lathe from 0.5” dia. stainless steel 303 rod, a coolant box made from 3/8” x 16ga square A-36 hr carbon steel tubing, two 8mm brass threaded adapters attached with Omega bond 200 2-part water sealing thermally conductive epoxy, and 1” fiberglass insulation tape wrapped around the coolant tube. A simplified drawing of this assembly is shown in Figure 2.

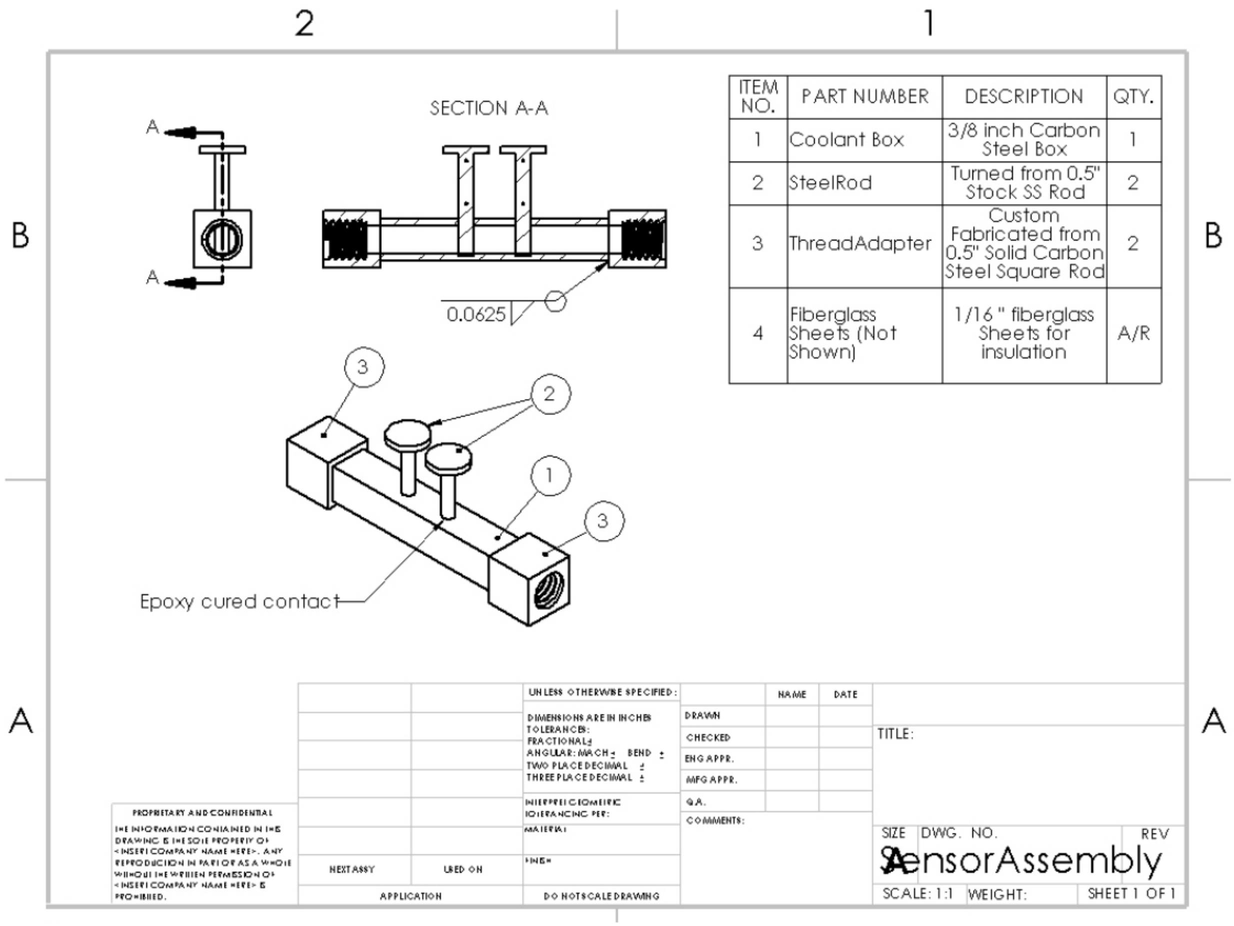


Figure 2: Drawing of Phase 1 Sensor Prototype

Once assembled, the design of this phase 1 prototype presented a few problems in assembly and use. It was difficult to connect the coolant tube to the thread adapters so that the square edges lined up precisely to prevent leakage- a fixture was developed in the Mechanical Engineering Student Machine Shop to help with the alignment. The fiberglass tape was not able to be arranged and attached in a layered configuration as originally intended, so it was simply wrapped around the sensor body which caused the sensor to be flimsy and difficult to handle. This also posed a problem for the data collected because the pin bodies were not completely insulated and thermally isolated from the oven environment, therefore heat was entering the system through more than just the pin heads. Pictures of this final prototype assembled are shown in Figure 3. Solutions to these problems as well as additional design improvements were the focus of this work, and those results are presented in the following thesis chapters.

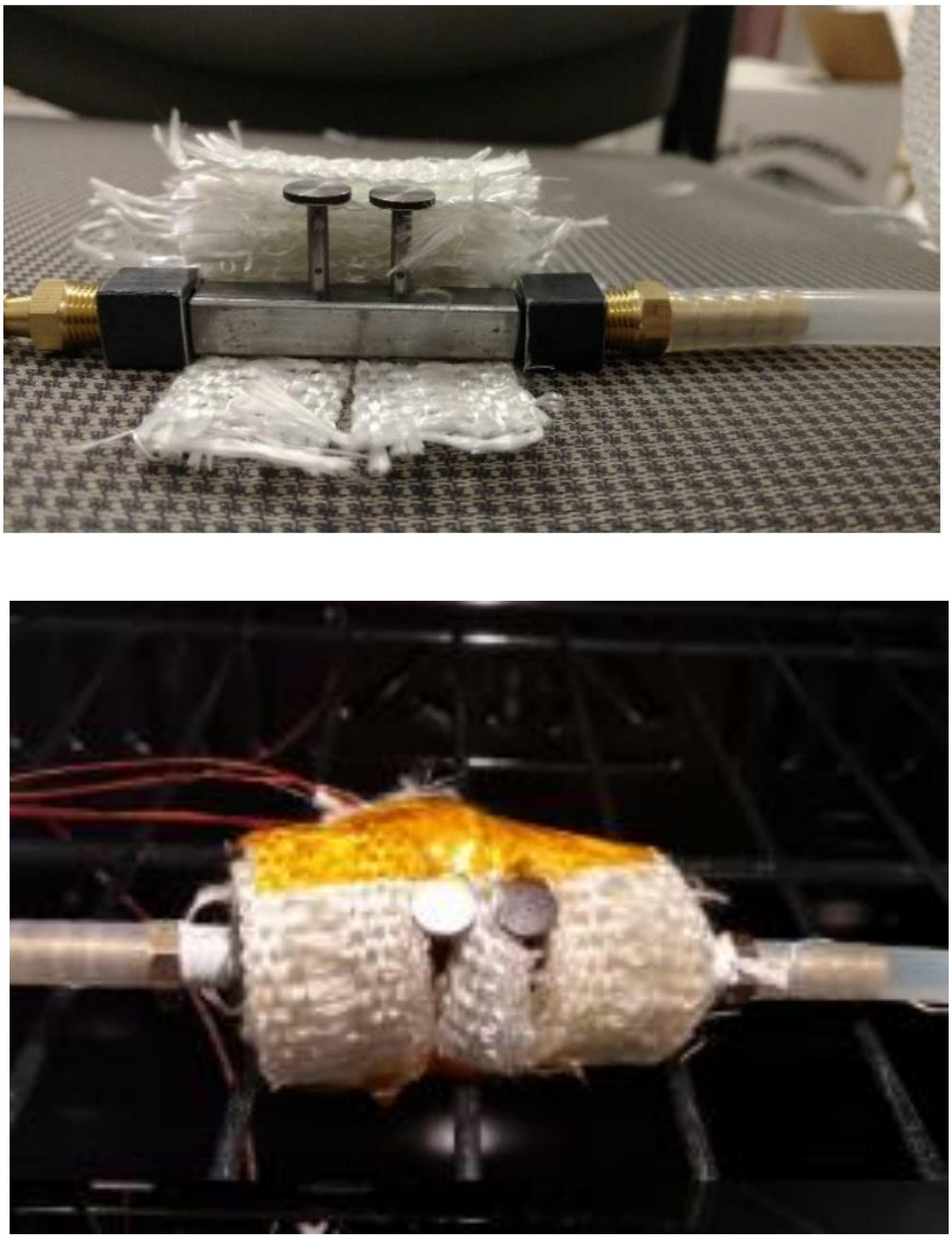


Figure 3: Assembled Phase 1 Sensor Prototype

In summary, the targeted components of the phase 1 prototype shown above that have been revised in phase 2 are the insulation, low emissivity pin coating, sensor body, user interface, and data acquisition system. Chapter 3 outlines the changes made to the first 4 components and Chapter 4 discusses the circuitry designs for the custom data acquisition system that replaces the one used in phase 1. These chapters discuss the problems faced at a deeper level as well as the design thinking process used to reach the solution chosen.

Chapter 3: Sensor Body Design Process

The sensor body of the phase 1 prototype had a few significant shortcomings as mentioned in the previous chapter. The fiberglass tape that was used as insulation around the pins and coolant tube was not stiff enough to use in a layered configuration, as initially intended. Therefore, the tape was wrapped up around the pins in a circular fashion, but unfortunately this method of attachment did not allow it to be tightly and securely connected and it also did not cover the body of the pins completely. Another problem with the use of fiberglass tape is that it cannot be handled with bare hands because it causes skin irritation.

The low emissivity pin top was polished with the intent of achieving a low emissivity constant, but as shown in Suraj's later results this method of polishing was not able to achieve a sufficiently low emissivity coefficient value. Finally, the combination of hose barbs, washers, and steel tubing that together formed the coolant cavity was difficult to assemble and rusted on the inside, causing the plastic tubing to also fill with the rust residue and become brittle. The high heat epoxy between the hose barbs and the connectors became brittle as well because of this and began to fail. An alternative design was therefore necessary in order to address these problems and create a durable sensor that can be used routinely in GE Appliance's testing labs.

3.1 Insulation

3.1.1 Problem Definition

The insulation around both sensor pins must have a thermal conductivity of less than 0.3 W/mK to align with the thermal models developed in phase 1. The material must be able to withstand 500 °F for at least 30 minutes and be rigid enough to provide support for the other components of the sensor.

3.1.2 Ideation of Potential Solutions

Three main methods of manufacturing were evaluated for fabrication of the insulation to fit the performance requirements: machining, injection molding, and 3D printing. High temperature ceramics and certain types of silica foam exist that can be machined on a standard CNC machine like the ones available in the OSU ME student machining lab. These high temperature, machinable materials have very low thermal conductivity values and can withstand temperatures much higher than 500 °F, but the geometry is limited by the manufacturing method and as a result small, complex internal features such as those required for proper thermal behavior of the system are not be feasible.

High temperature polypropylene and PEEK materials can be injection molded into a machined mold, but again the geometry of the part is constrained by the limits of the CNC machine that creates the mold (meaning that small internal channels to hold the thermocouples in place cannot be created). Another significant downside of injection molding is that even the high temperature materials that are available have a melting point close to 500 °F, which could cause the material to become soft and change the insulation properties during a test that involves temperatures near this value. This is because the material must be heated to a near liquid state by the injection molding machine, and as a result material that melts at very high temperature is unique and very expensive.

The last available method of manufacturing the insulation is 3D printing and this same fact is true- it is difficult to find higher temperature materials because of the nature of the process. Two groups of material – Ultem and Metal – can be 3D printed at temperatures around 550 °F and above which meet the requirements for this application. 3D printing is an advantageous process because the internal geometry of the insulation can be very complex, providing structure and support to the other components within the sensor. Small internal features can be easily created, and tolerances can be very precise when using this method, depending on the 3D printer used. All the methods and material samples mentioned above are shown in Figure 4.

Figure 4: Insulation Manufacturing Methods and Material Choices [5]

The procedure to determine which manufacturing process and material to use was lengthy. First, a broad search was conducted to understand the materials on the market that meet the specifications necessary for the sensor insulation. Data sheets were collected and vendors contacted regarding the cutting edge materials that that fit, such as rescor glass ceramic and fused silica foam. It became obvious that these materials were out of budget for this project, and most of the materials required the use of specialized equipment that is not at the available at either the Ohio State Mechanical Engineering labs and the GE Appliances prototype lab. Machining and injection molding were both ruled out as viable manufacturing processes as a result.

3.1.3 Prototype

The focus was turned to conventional materials that are more readily available here in the OSU labs for 3D printing, since these are cost effective and accessible. A prototype of the sensor insulation could be printed with the OSU equipment and tested at low temperatures. The GE Appliances Prototype lab has the ability to 3D print the sensor insulation using high temperature materials - such as Ultem - that can withstand the temperatures above 500°F for more than 30 minutes. This is a great advantage for GE Appliances since they can print the sensor body in-house and potentially save money and time as compared to having the sensors fabricated by an outside supplier. In order to test the viability of the design, a prototype block was printed out of simple ABS plastic which has a glass transition temperature of approximately 320 °F, and the sensor pins were inserted, ensuring the proper tolerances and fit.

Collars around the thermocouple channels were added to the insulation configuration to ensure that the thermocouples would not become dislodged from the pins when moved. As mentioned previously, 3D printing the insulation material resulted in a more rigid structure and as a result provided better protection to the thermocouples from bending fatigue in the wires. This is a common problem with thermocouples that can result in an open circuit and sensor failure

The temperature is measured at the top and bottom of each pin using the same thermocouples as the initial prototype sensor. This initial test in room temperature conditions demonstrated that this body design was capable of structurally supporting the coolant tubes and the thermocouples while still providing usable data. A picture of the fully constructed sensor is shown in Figure 5.

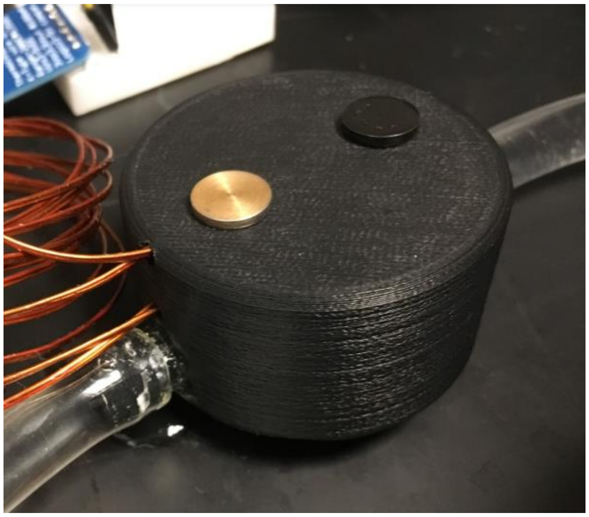


Figure 5:Fully Assembled Sensor Body

3.2 Low Emissivity Pin Coating

3.2.1 Problem Definition

In the MATLAB model developed by Suraj in phase 1 an emissivity coefficient of 0.3 was chosen and in the simulation conditions 0.05 was used to emulate the polished gold on the top of the RC01 sensor. The low emissivity pin on the original phase 1 prototype was polished progressively with two different levels of abrasive particle sized sandpaper (240-grit followed by 1200-grit). This produced an emissivity coefficient between 0.3-0.5, which was not low enough to attain heat flow conditions through the pin that primarily involved only convective heat transfer with minimal radiative heat transfer.

3.2.2 Ideation of Potential Solutions

It was hypothesized that to achieve the surface finish needed to have a low emissivity coefficient, the abrasive particle sizes of sandpaper used in subsequent polishing operations must be stepped up in finer increments. The 240-grit sandpaper has much larger particle size, and therefore it produced a fairly rough surface finish on the pin. Following that immediately with the much finer abrasive particle size of the 1200 grit did not result in a proper surface finish, as shown in Figure 6-2. Therefore 2 identical pins were polished using successive steps of sandpaper with smaller increments of change in the abrasive particle size, as well as two different methods of application: polishing cotton and a Dremel polishing end (shown in Figure 6-3, 6-4 respectively). A control pin with no polishing was also included in the testing shown in Figure 6-1. Finally, at the conclusion of phase 1 it had been recommended that after polishing the pin should be coated in a thin layer of a material known to have a low emissivity coefficient. Gold was chosen because it has an emissivity coefficient of 0.05 when polished, and the finished gold-coated pin is shown in Figure 6-5.

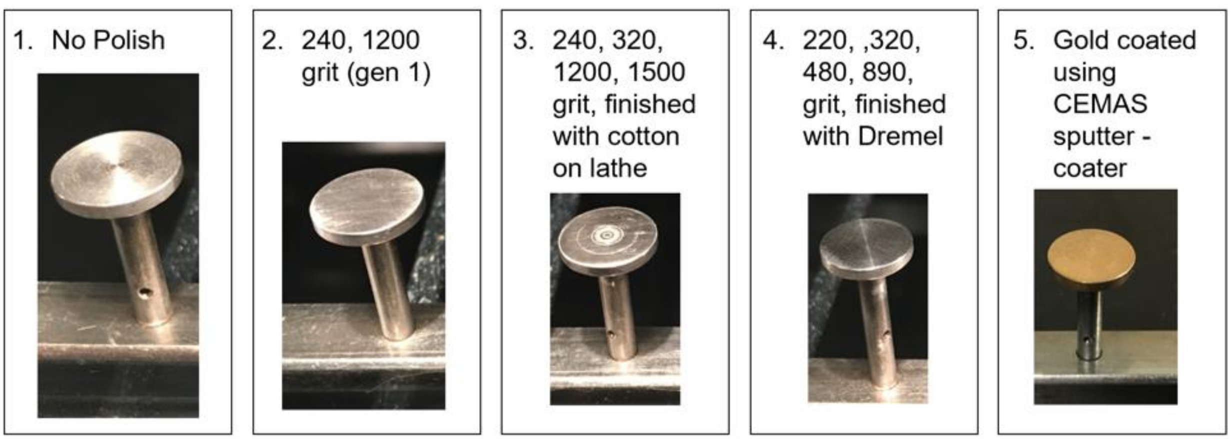


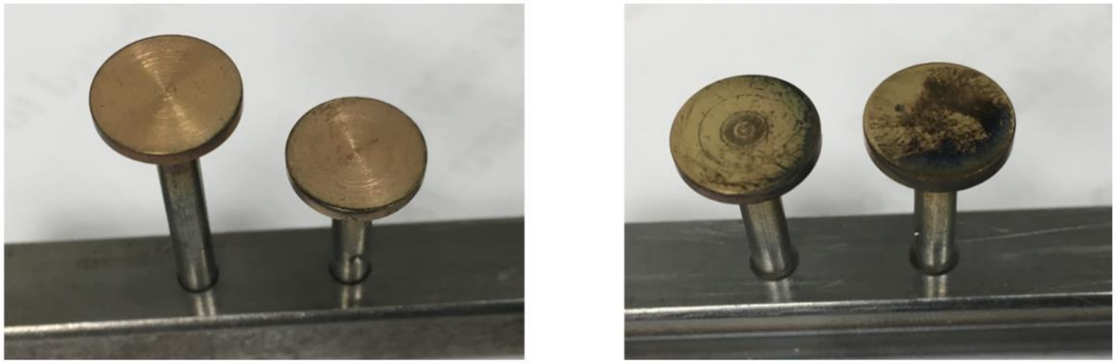
Figure 6: Low Emissivity Pin Polishing Options

These 5 pins were tested to evaluate the emissivity constant using the Fluke 62 Max+ IR thermometer (Figure 7) and an incubator. The incubator temperature readout had a precision of 1° and an accuracy of +/- 2° and the temperature gun had a precision of 0.1°C and accuracy of +/- 1.0% of reading over 100°. The incubator was heated to 350°F with the pins inside and allowed enough time to reach a steady temperature, about 30 minutes. Then the temperature of each pin was measured with the emissivity set to 0.5 on the IR gun. The emissivity was then adjusted on the gun for each separate pin until the temperature readout agreed with the incubator oven temperature probe. While this method is not the most precise, it was enough to confirm that pins 1 and 2 had a high emissivity coefficient of 0.5 or greater, pins 3 and 4 had an emissivity coefficient near 0.3, and pin 5 had a lower emissivity coefficient of approximately 0.1. Therefore, the gold-coated pin was chosen for the stage 2 sensor design. Another benefit of using a gold-coated pin is increased durability as compared to stainless steel. The polished stainless steel scratched easily.

Figure 7: Testing Equipment for Emissivity Coefficient

3.2.3 Prototype

The gold coating was applied using the Leica ACE600 Sputter Coater in OSU's Center for Electron Microscopy and Analysis (CEMAS). 4 pins were inserted into the machine's holding plate and it cycled for 8 seconds, providing an extremely thin layer of gold. 2 of the pins were polished prior to the coating and 2 were left unpolished to test the best conditions for the gold to adhere to the surface. The 2 unpolished pins had a superior surface finish shown clearly in the resulting pictures in Figure 8. Although all 4 pin surfaces were cleaned well before the coating, it is suspected that the polished pins had oil or some residue on the surface that also contributed to the uneven coat.



Only Gold Coat   Polished + Gold Coated

Figure 8: Results of Gold Sputter Coating on Pins

3.3 Coolant Cavity and Body Re-design

3.3.1 Problem Definition

The original sensor body was flimsy due to the fiberglass insulation tape. This caused the thermocouples to easily come detached from the pins and the sensor to sit at an angle on the oven rack. The basic sensor structure with coolant tube at the base, pins side by side near the center of the sensor, thermocouples attached to the pins perpendicular to the surface, and insulation surrounding all components was used again for this phase as to not deviate from the design constraints determined in phase 1.

3.3.2 Ideation of Potential Solutions & Prototype

The final sensor body design, as modeled in SolidWorks 2018, is shown in Figure 9. The first image, with hidden lines displayed, shows the 4 channels through which the thermocouples attach to the pins from the left side of the sensor body. The coolant channel is also built into the sensor structure with 3D printed hose barbs so as the eliminate any risk of rust of leaking from internal components in the sensor.

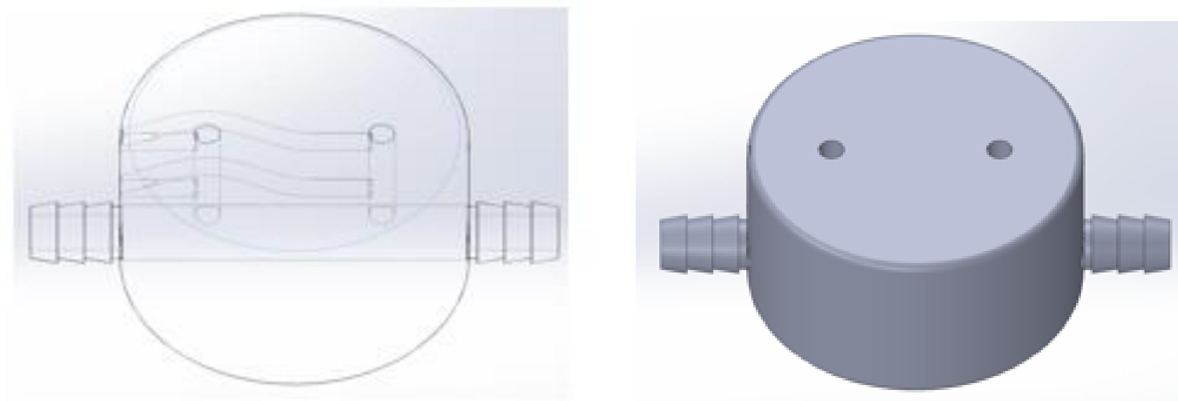


Figure 9: Sensor Body Solidworks Images

In addition to the features mentioned above, the part is designed in such a way that it does not need an internal support structure when it is printed, minimizing cost and postproduction time. The thermocouples and pins fit securely due to the tolerances that can be achieved with the Ultimaker 3 Extended FDM printer and the resulting part can be easily assembled. This phase 2 body design has half as many components as the phase 1 design, therefore reducing complexity and minimizing the possible error in assembly. The less error that exists in the assembly process, the less error and measurement variance that will result in each sensor. This is extremely important to the testing lab at GE Appliances and was stressed as a major design requirement for the phase 2 sensor.

Chapter 4: Data Acquisition Design Process

4.1 Component Selection

Thermocouples are the preferred temperature measurement method for many reasons. They are low cost and reliable devices due to their simple nature and provide consistent performance over time. They are accurate and repeatable, capable of up to 0.1 °C accuracy with proper calibration.

A thermocouple is a type of temperature sensor created by joining two wires made of dissimilar metals. This connection causes a slight voltage across the wires that increases related to the temperature of the junction, known as the Seebeck effect. K type thermocouples are made of Nickel-Chromium and Nickel-Aluminum wires are used in this sensor because they have a wide temperature range (-100° to 500°C) and are easy to interface with. The voltage change measured across the thermocouple is very small, around 41 μV/°C, so the measurement sensitivity is determined by the choice of interface chip that is used to amplify and process the voltage signal. Additionally, the effect measured is differential temperature, not absolute, and a reference temperature thermal mass of some type must be used to determine the absolute temperature value; this is known as cold-junction compensation.

There are also drawbacks associated with using thermocouples for temperature measurement. The output voltage is very small, and in most cases, it is not linear and must be calibrated to correct for this. Thermocouples need to be electrically insulated from their surroundings because of the vulnerability of the signal- it is such a slight voltage that it is very susceptible to interference from other signals. The time-constant, or response time, is a function of the thermocouple's mass therefore the longer ones may take seconds to output a voltage change. When thermocouples are connected with other circuitry, the connection point creates another ‘thermocouple’ with the joining of those two dissimilar materials and therefore it needs to be compensated for. Finally, thermocouples are easily subject to bending fatigue and can easily break, resulting in an open circuit.

Given these issues associated with thermocouple use, the thermocouple interface circuitry must address these issues in order to provide accurate data. The goal of interface circuitry is to take the small voltage and linearly amplify it at a constant gain regardless of signal level to a higher voltage while also incorporating cold junction compensation to output an absolute temperature. There are many thermocouple interface chips on the market that can achieve this and additionally can convert the analog signal to a digital format. After investigating many of these, it was determined that there were three products that would meet the functional requirements, and they were evaluated to determine the best option for this application. The AD 594 is a simple chip previously used in ME 3870 with a precision of 1°C [3], the TE MSP432 was developed last year for high temperature applications and is a bit more complex, and the MAX31855 [4] is an extremely popular chip that is accurate to 0.25°C. The MAX31855 was chosen due to its superior accuracy and the wealth of information, tutorials, and examples available online. This chip is popular because it has been proven to be durable, accurate, and easy to use. All of the thermocouple interface chips available for hobbyists are designed for one thermocouple only, therefore the custom circuit must include one interface chip for each thermocouple. This introduces price and space concerns.

Multiplexers are a simple component that can easily provide the interface to switch between data lines. In addition to the space problem addressed previously in the need of one interface chip per thermocouple, this also means that each thermocouple requires one data line. If multiple sensors are used at the same time and there are 4 thermocouples per sensor, it is not feasible to have one separate data line for each thermocouple because most microcontrollers do not have that many input pins. A multiplexer could be placed either between the thermocouples and the interface chip, reducing the number of interface chips needed, or after the interface chips and before the microcontroller to consolidate the number of data lines to just one. Differences in performance due to the switches in the multiplexing circuitry may introduce small errors in voltage readings directly from the thermocouples, which are already very small in magnitude. This configuration would therefore have the potential to introduce a large level of error when the signal is amplified, so it was decided to place the multiplexer after the interface chips. When selecting a multiplexer, it is important to consider the directionality of the signal, the speed needed when switching lines, and the number of lines from the microcontroller used to control the direction. With help from Dylan DeSantis, the CD4052 multiplexer was selected. It has 2, 4 channel groups and is controlled by A and B selection lines from the microcontroller. They can be easily combined with each other in the case that multiple sensors are used at the same time.

The microcontroller selection process also followed a similar path, with an initial screening process used to determine the appropriate candidates followed by a final evaluation of those potentially applicable devices. The Arduino portfolio of microcontrollers was ruled out because of their limited IDE. Arduino is a simple microcontroller designed to run one program over and over and it cannot process graphics well. The Raspberry Pi is a full-fledged microcomputer capable of running multiple programs at a time and it has an integrated graphics card, therefore the Raspberry Pi line of microcontrollers was the clear choice. Initially the RPi ZeroW was chosen because of its small size and low price while still providing the possibility to connect wirelessly. After it was decided by GE Appliances that it was preferable to have the heat flux data output to a flash drive rather than transmitted through WIFI or Bluetooth, the RPi

3 was used because the smaller size was not necessary and the RPi 3 was more readily available in the lab. In reality, any RPi can be used because this is a very simple concept that uses just a few SPI pins, GPIO pins, and the 3.3V and 5V power sources.

4.2 Circuit Design

The custom circuitry described above was first prototyped on a breadboard and tested in a room temperature setting. It is capable of amplifying, linearizing, and converting the signals from one sensor (4 thermocouples). The initial breadboarded layout is shown below in Figure 10.

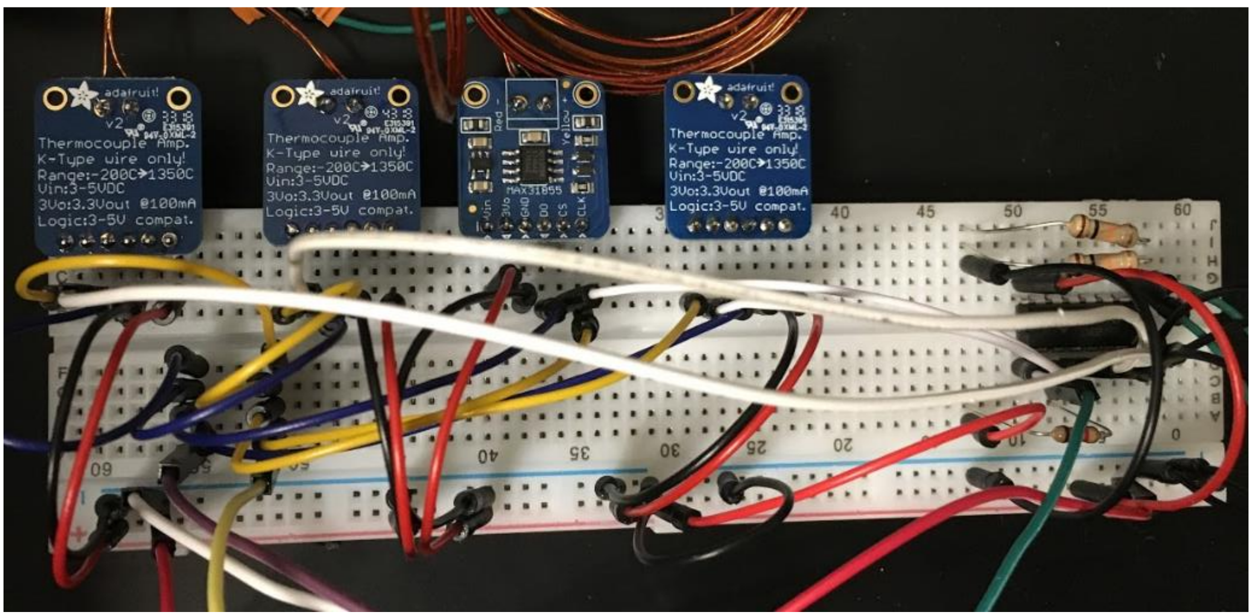


Figure 10: Breadboard of Custom Circuit

Once the circuit was tested and the proper functionality verified, it was laid out in KiCad, an open source software for electronics design. The schematic was created (shown on the next page in Figure 11) with a goal of processing the data while minimizing the risk of power spikes by using capacitors between the thermocouple ends and resistors linking the A and B select lines to ground. The thermocouples connect to the 4 screw terminals on the left side of the diagram, which then each run to the MAX31855 chip, which then connects to the Raspberry Pi (bottom right) and the CD4052 multiplexer (top right).

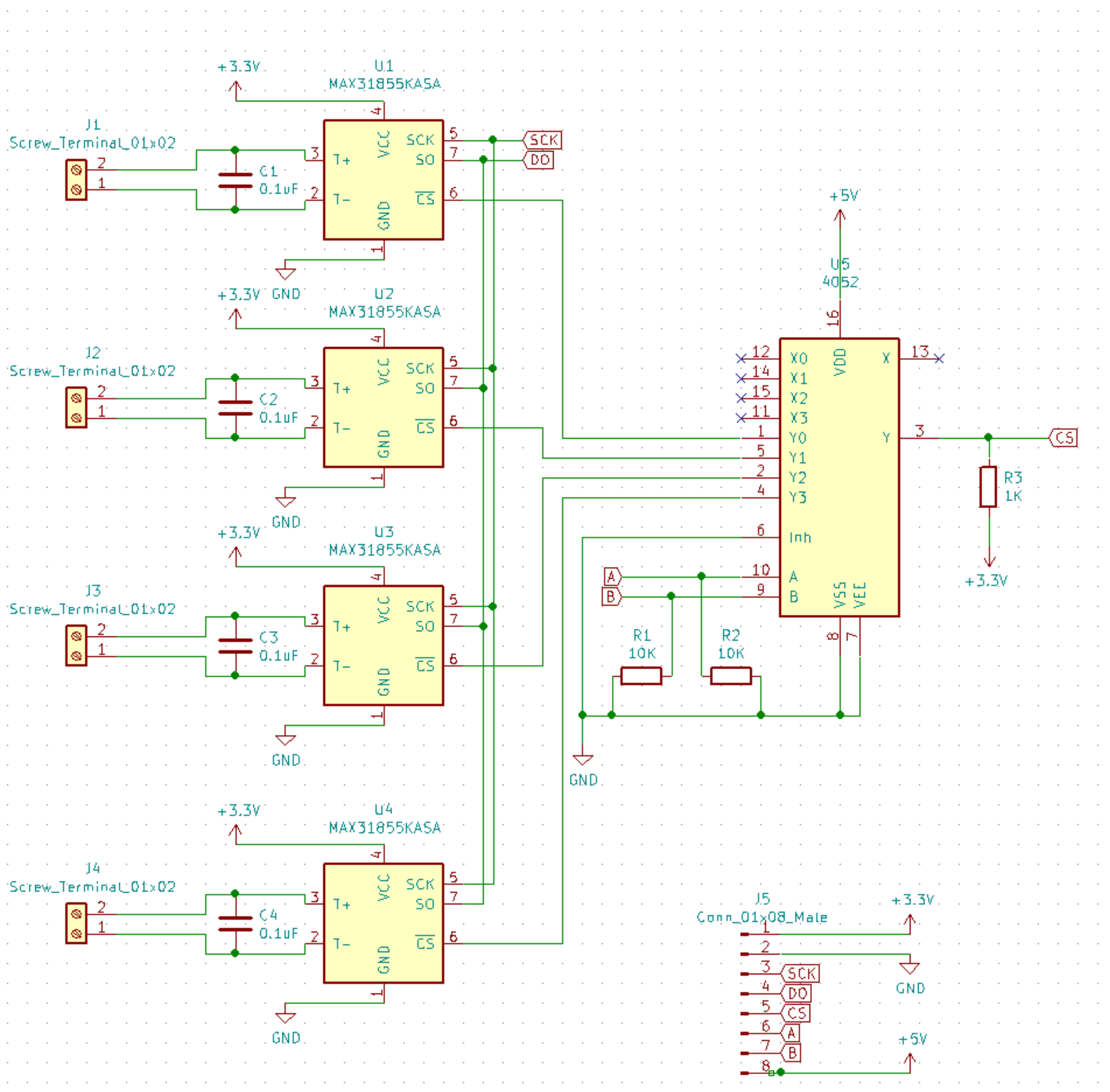
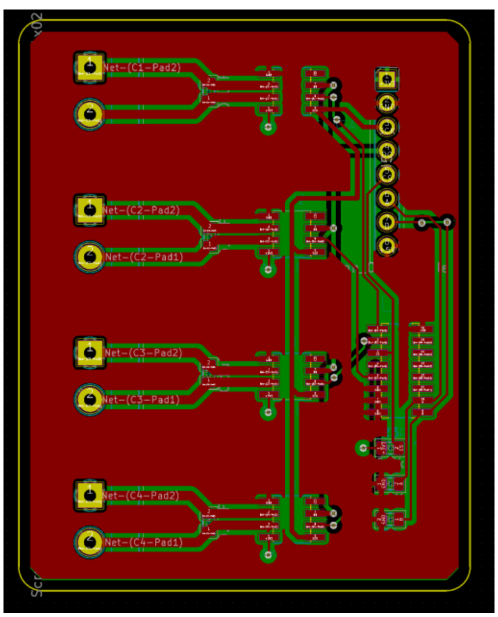


Figure 11: Schematic of Custom Circuit

The schematic was checked for errors using the Design Tools Editor in the software, which simulates the power and signal flow through a circuit with the goal of exposing any incorrect connections or loose ends. Next the PCB layout was created from the schematic. KiCad provided the ability to create multiple layers within the board, which was helpful for power management because the ground and power layers could be separated. This is desirable because, especially on such a small board, there is a risk that the power and ground could be accidentally connected and short the circuit. The separation of these layers minimizes this chance. On the following page, Figure 12-1 shows the top power layer of the custom board with red traces connecting the components. The board design followed directly from the schematic. The screw terminals were placed on the left side of the board to allow the thermocouple wires to be easily attached. The MAX31855 chips were placed close to the thermocouples to minimize the distance for the signal to travel before being amplified. The board pinout was placed in the upper right-hand corner to separate it from the thermocouple wires. KiCad also is able to generate a 3D model of the prototype board, which is shown in Figure 12-2.

(1) 

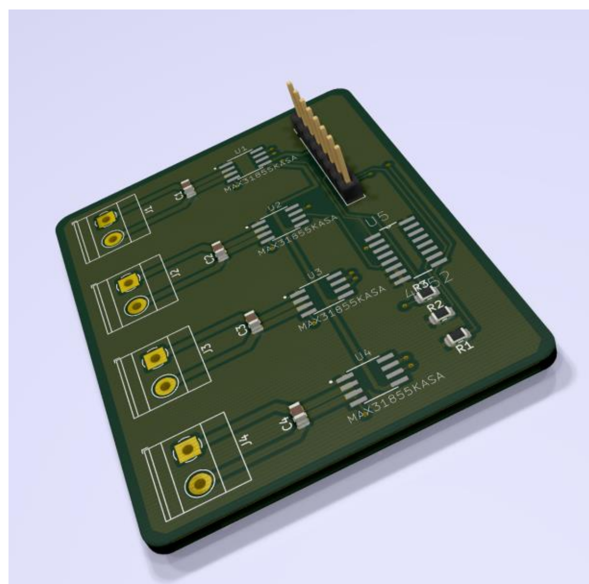
(2) 

Figure 12: KiCad PCB Layout and 3D Board Rendering

Using the schematic and PCB board layouts created in KiCad, three prototype boards were ordered from MacroFab. The Macrofab website requires the user to select all board components through their own online inventory. It is critical to double check the dimensions and pinout of every component to ensure it matches the components used in the KiCad board design. Once the PCB footprint is created and the through holes drilled, the board cannot be edited by hand if a component doesn't fit. The price per prototype board was $119.20.

Once the boards arrived, they were tested to make sure all connections were secure and correct. First a single board was connected to the Raspberry Pi to test the functionality, and then all three connected to validate the accuracy and repeatability of the sensor itself. Figure 13 shows a picture of the final board.

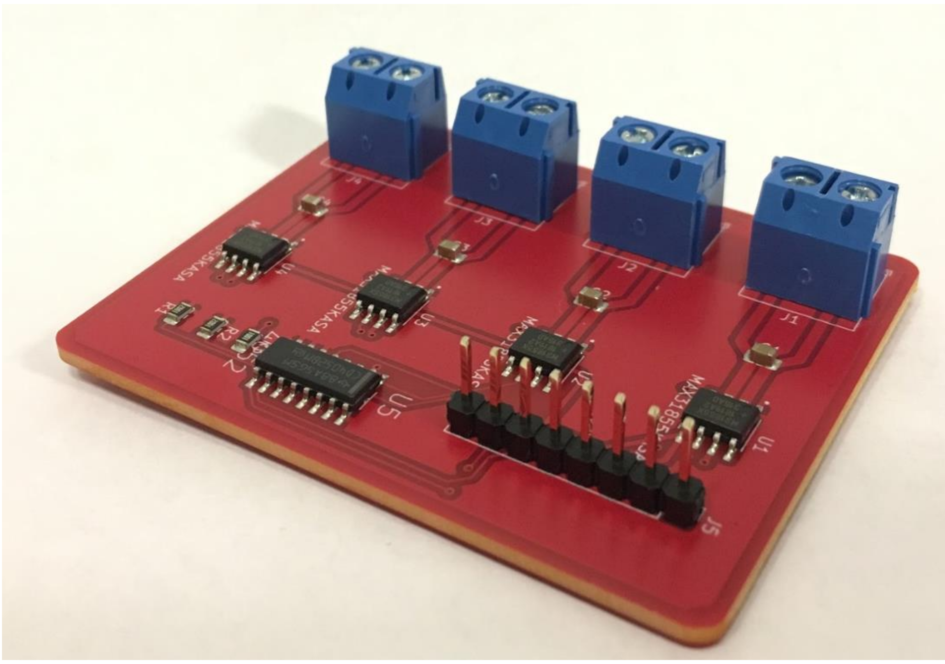


Figure 13: Custom Circuit for Sensor

To control the sensors, a simple python code is used on the Raspberry Pi. The code can be run automatically upon startup of the pi or selected at any time from the home screen of the Raspberry Pi. When the program launches it begins taking readings of the voltage levels for all 4 thermocouples and recording them to a .csv file on an SD card onboard the Raspberry Pi. The data collected from the thermocouples can be plotted on a graph to show the real time temperature values if the user chooses to do so. This can be accomplished by running a second program as the data is being collected. Once the test is suspended, the .csv file is saved to an external flash drive and can be exported to Excel or any other data analytics program.

External libraries for the MAX31855 thermocouple chip were used in the python code to shorten the length of the program and simplify the logic for any edits or additions necessary in the future of this project. The goal for the code was for it to be straightforward to streamline the sensor design process in the future. To achieve this, it utilizes two libraries (one for the MAX31855 chip and one to write to .csv files) that significantly shorten the code and provide functions that are intuitive to use. The code is also commented extensively and organized into sections for each task. It can be easily edited to accommodate for multiple sensors powered by the same Raspberry Pi.

Chapter 5: User Interface Design Process

5.1 Problem Definition

The user interface was the facet of the sensor that underwent the most drastic changes during phase 2 of the project. Initially, there was a heavy focus on the sensor and all its components (circuitry, controls, power) to only exist inside the 3”x1”x1” boundary that was set in the initial design requirements. This meant that it was necessary to have a thermocouple amplification and A/D converter chip that could withstand the high temperatures inside the oven. It was also necessary to have a Bluetooth or similarly wirelessly enabled chip that could withstand those temperatures and transfer the data through the metal walls of the oven. There were no products on the market that could fulfill these requirements without far exceeding the cost requirement per sensor.

5.3 Ideation of Potential Solutions

Moving the control circuitry for each sensor outside of the oven created the freedom to choose from many cheaper, more versatile components. While it was still possible to transmit the data wirelessly (via Bluetooth or WIFI) with this new setup, the GE Appliances team decided that they would rather transfer it from the Raspberry Pi to their lab computers by USB for now because of the complex security requirements in their internal network. It was desirable to see the data collected graphed live, therefore the touchscreen was added to enable control of the sensors while the test is running. This ensures that the GE Appliances team can have maximum control over the sensors and will be alerted as soon as possible if any of the sensors is returning an incorrect or null value.

The fact that each sensor has its own individual circuit board allows the team to utilize any number of sensors at the same time for their oven testing. The circuit boards are simple to combine and can be stacked below the touchscreen and Raspberry Pi setup for storage. This was important to the GE Appliances team because they desire to use arrays of sensors (similar to an array of cookies on a tray) to test the heat flux in many parts of the oven at once. During their food testing that have found that sometimes cookies on one side of the oven can bake very differently than ones on the other side, therefore it is important to identify this distribution of the heat flux and correct it. No one wants a tray of unevenly baked cookies or a pot roast that's only done on one side!

5.3 Prototype

Below, Figure 14 shows the final concept for the sensor user interface. The coolant is powered by a small pump, replacing the system powered by a faucet used in phase 1. The sensors all share the coolant, which runs back into the same tank. It will be shown in the following section on testing that at low oven temperatures the water temperature does not rise enough from start to finish to have a significant effect on the temperature at the bottom of the pin. The touchscreen and control circuitry are all mounted on the oven wall, connected to the sensors only by the 4 thermocouple wires coming from each sensor.

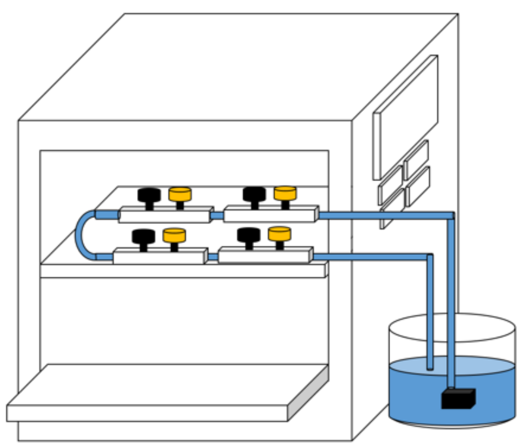


Figure 14: Concept Drawing for the Sensor User Interface

A picture of the experimental setup for the sensor is shown below in Figure 15. The bill of materials can be found in Appendix A.

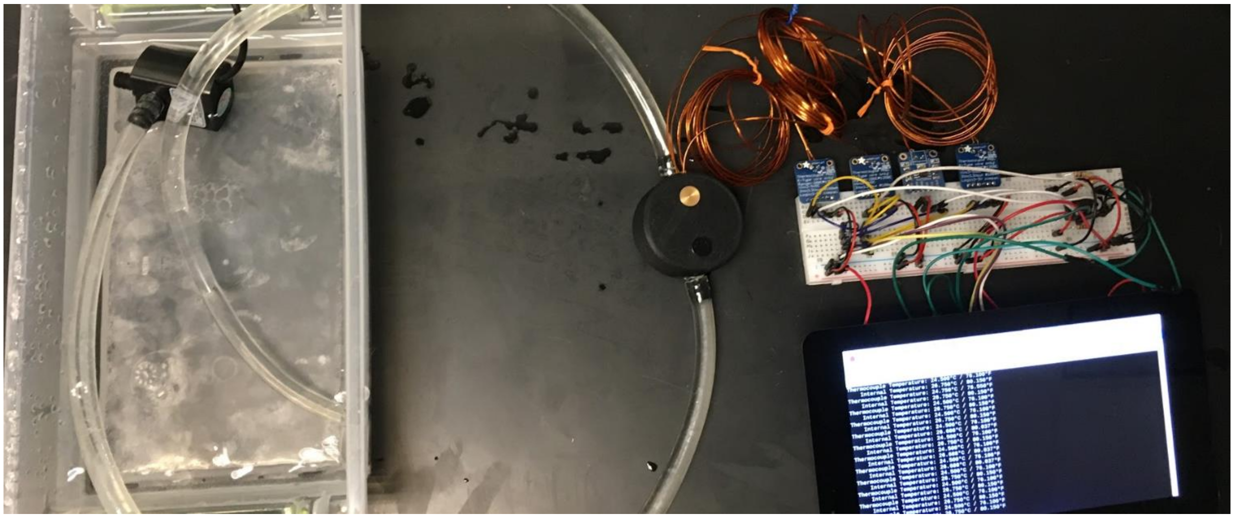


Figure 15: Experimental Setup of the Heat-Flux Sensor

Chapter 6: Sensor Testing

6.1 Functionality Test 1

Using the experimental setup detailed in the previous section, the sensor and corresponding circuitry were first tested for functionality. The oven was set to 200°F due to the low melting temperature of the ABS plastic in the sensor body. The purpose of this first test was only to prove functionality of the sensor and its components. The results are shown below in Figure 16.

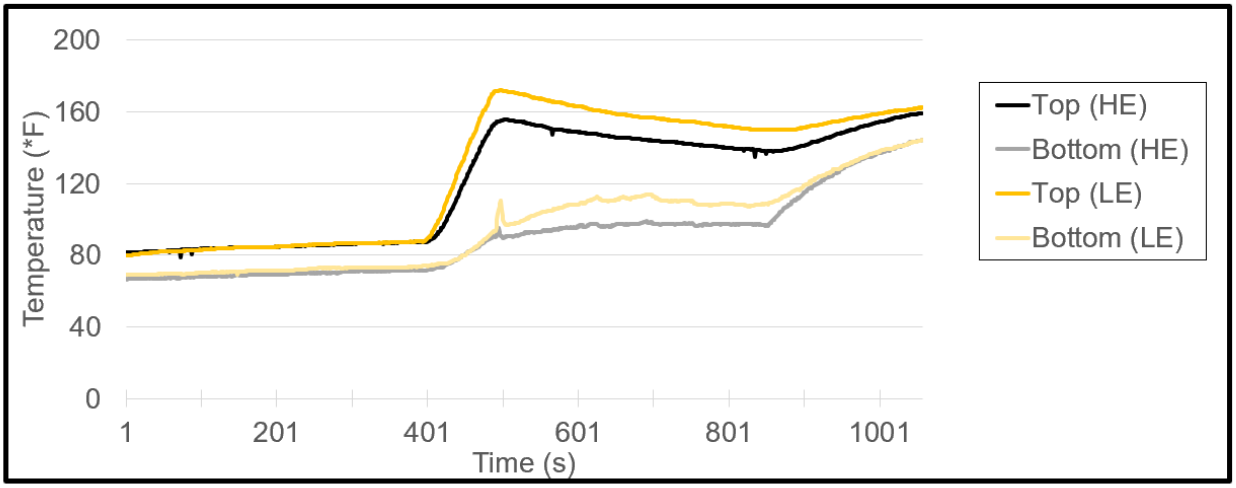


Figure 16: Initial Functionality Test Results

The gold and yellow lines in the figure represent the top and bottom of the low emissivity (LE) pin while the black and grey represent the top and bottom of the high emissivity (HE) pin. The oven was turned on at 400 seconds and reaches steady state around 500 seconds. Unfortunately, the coolant pump batteries died around 850 seconds which causes the steep rise in temperature for all 4 thermocouples and the loss of any temperature difference. The test was suspended shortly after. It is interesting to note the shape of the temperature curves during the time that the oven is in steady state- these match the shape of the temperature curves predicted by Suraj’s initial simulations.

6.2 Functionality Test 2

The functionality test was repeated to verify the results found above and better define the temperature difference between the top and the bottom of both pins over a long period of steady state inside the oven. The same test was run again at 200°F but this time the data collection began once the oven temperature reached steady state. The test was then run for 30 minutes and the results for each pin are shown separately below in Figure 17and Figure 18.

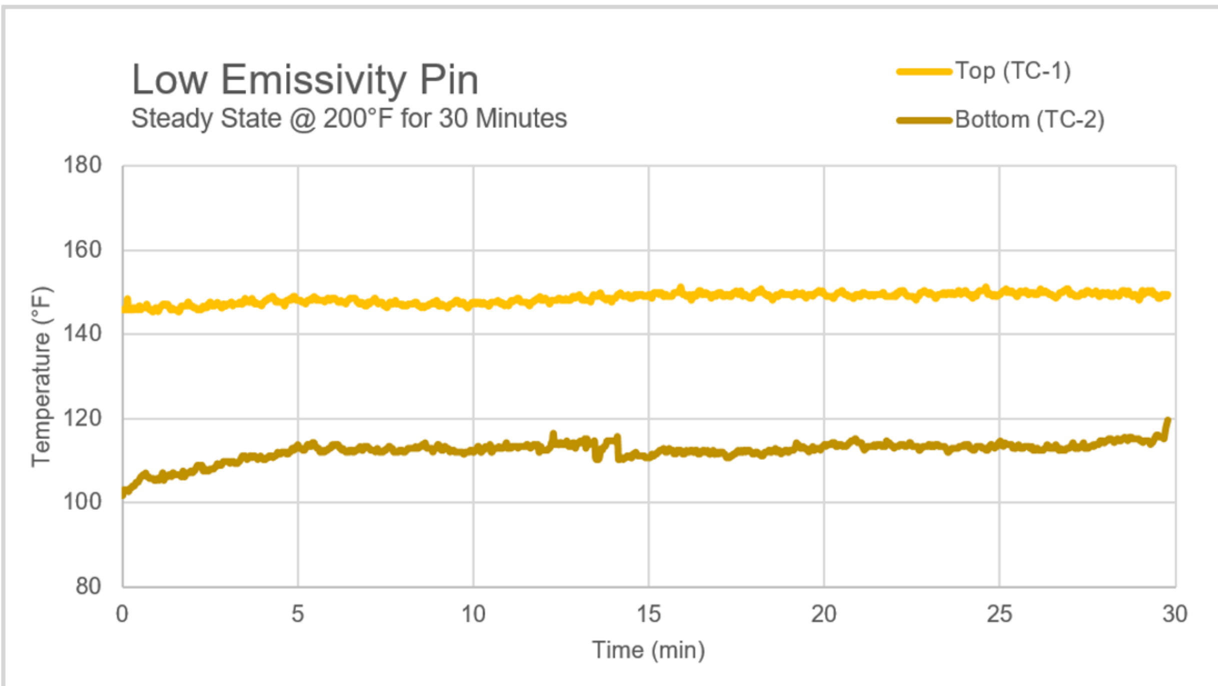


Figure 17: Second Functionality Test of Low Emissivity Pin

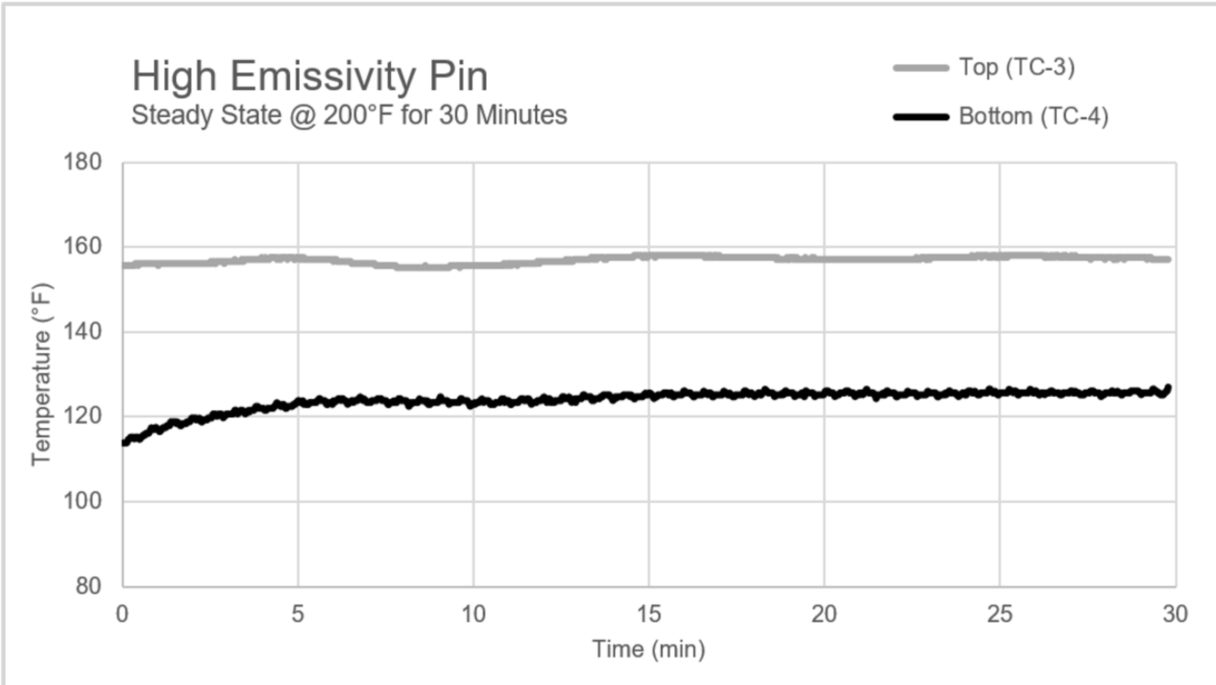


Figure 18: Second Functionality Test of High Emissivity Pin

This second test clearly shows the large differences in temperature between the top and the bottom of the pins- about 30° for the low emissivity pin and 25° for the high emissivity pin. This is anywhere from 2 – 6x the temperature difference achieved using the phase 1 prototype, which also varied extremely while a comparison between both the first and second tests show that the temperature difference is quite steady.

6.3 Sensor Cost

Table 1 shows the final cost for each component, divided into components needed for each sensor and components needed only once for each oven. The total cost for the chosen configuration can be calculated by multiplying the number of sensors desired in one oven by the sensor total cost and then adding it to the cost for the one-time components.

Table 1: Cost of Heat Flux Sensor

Components used in Each Sensor				
Item	Description	Cost	Quantity	Total
Stainless Steel pin	Fabrication through Ohio State Mechanical Engineering Machine Shop	$35	2	$70.00
Low emissivity gold coat	CEMAS gold sputter coat machine	$30/half hour	1	$30.00
High Emissivity black enamel	Engine Enamel gloss black spray	$5.48	1	$5.48
Sensor Body	3D printed through GEA Prototype Lab	-	1	-
Thermocouples	Kapton insulated, K type, 30 gauge, 2-meter length	$11.48	4	$45.92
Custom PCB	Ordered through Macrofab.com	$119.20	1	$119.20
			Subtotal	$270.60
Components used in each oven				
Water Pump	12V Velleman Pump	$24.99	1	$24.99
Tubing	1 ft 8mm ID plastic tubing	$10.95/10ft	1	$10.95
Raspberry Pi 3	Model B+ with 2.5A power supply	$38.10	1	$38.10
Touchscreen	7” touch display HAT for RPi	$79.99	1	$79.99
			Subtotal	$154.03

Chapter 7: Discussion

This project encompassed the entire design process and resulted in the combination of many elements to create the final sensor design. Throughout this time there were iterations on each component and the final design, and the improvements should not stop at the end of this phase. Below are my observations, recommendations, and reflections on the final design reached.

7.1 Design Observations and Recommendations

First, the material for sensor body remains undefined. Ultem has been identified as the most viable option but has not been prototyped to confirm this hypothesis. The GE Appliances Prototype Lab has the ability to print using Ultem and other similar high temperature materials, not mentioned by name specifically thus far. It is assumed that the Prototype Lab owner, Nick Okruch, has the expertise in this field to provide usable material options for the sensor body that can then be narrowed down by the SIMCenter's oven simulation. It is important to note that the tolerances used in the phase 2 prototype were perfect for the ABS print on the Ultimaker 3 in the Ohio State Mechanical Engineering Smart Products lab but may not work as well on another make/model of printer with a different kind of material. When printing the sensor model in a new environment, the tolerancing of the holes should be tested first with a smaller sample to ensure that the pins and thermocouples will still fit.

The sensor body insulation design could possibly be studied further by varying the print properties to different infill percentages or even specifically designing the inside of the sensor to contain air pockets of a certain shape. It is currently not known how this will affect the measured temperatures, as all prototypes were printed at 20% infill. The sensor body design could be improved upon by incorporating a split of the part at the two heights of the thermocouple junctions, breaking the sensor into three separate parts and enabling the sure connection of the thermocouples to the pins. As the design stands right now, the thermocouples are only assumed to be touching the pins and it is not able to be verified because the body is one solid object. Layering the body at the specific pin heights where the thermocouples are connected would still produce a compact and easy to assemble sensor and it has the potential to greatly increase the accuracy of the measurements.

Another entirely new option for the sensor body is thermoset materials. These would provide an advantage because, once molded, they do not easily remelt (as opposed to the thermoplastics discussed above which do). Thermoset 3D printing technology is very new and has not yet been developed for commercial use, but injection molding thermoset materials is possible and could be achieved in GE Appliance's Prototype Lab.

The coolant tube through the body of the thermocouple does not leak, but the hose barb connection seems to fill with water when the pump is running. Teflon tape or a hose clamp can be added to the hose barb to combat this problem, as it is likely that this will develop into a leak with prolonged use. The type of coolant used has not been investigated in this project but could potentially be of great use. Particularly, the use of ice water in an effort to maintain a constant coolant temperature could be of some use to simplify the heat flux formulas and keep the system at 'steady state'. It would be important to understand if the current use of water with a varying temperature over the test duration detrimentally affects the accuracy of the heat flux measurements, or if it only decreases the precision as suspected.

Next, the data acquisition and circuitry components of the sensor had a few minor errors. The neck of the thermocouple holes in the sensor body have an interference fit with the thermocouple wires to ensure they cannot be easily pulled out, but the tip of the thermocouple can sometimes still come out of contact with the pin body due to the metal-metal contact (nothing to securely attach the two). When this happens, the thermocouple returns a NaN value to the Raspberry Pi and it is necessary to readjust it in the channel to ensure it is touching the pin. Ideally, the small holes in the pin where the thermocouples make contact should be filled with a sticky substance to ensure they stayed connected, but it is not known how or if this would affect the temperature measurement. Thermal paste, often used to connect heat sinks to electronics, could be a feasible option because of its high heat transfer coefficient but it also has the downside of not solidifying, therefore the thermocouples could still easily be pulled away from the pins. High temperature epoxy is another great option, but care should be taken in the selection of this because of its tendencies to become brittle with increased usage. The thermocouples could be coated with an electrostatically insulated material and then ‘welded’ to the pins as a surefire way to ensure the connection. A final suggestion for a solution is to build the pins using ultrasonic additive manufacturing, with the thermocouples physically embedded into the pins.

The custom data processing PCBs all connect to the same single DO and SCK lines coming from the Raspberry Pi. The strength of the signal will decrease as more sensors are added to this circuit, and it has not been determined at which limit this becomes detrimental to the function of the circuitry. It is recommended to check the function of all sensors in the circuit when each additional sensor is added.

The three PCB prototypes were ordered from Macrofab.com. The process of uploading the necessary files from KiCad proved difficult because KiCad does not create a separate file with the X and Y locations of the components on the board. While Macrofab says that it accepts KiCad file formats, an email from the help team confirmed that this is an unresolved issue on their end. The solution was for the help team to recreate the file themselves, which took 24 hours. In addition, the bill of materials created in KiCad does not copy over automatically so every component had to be selected from Macrofab's internal library which was poorly labeled and organized. By my own error, I chose two components incorrectly- a 2x4 header pin instead of an 8x1 and a 2.54mm screw terminal instead of a 5.00mm size. This error caused a 10-day delay in production despite the fact that I emailed the corrections the same day that the error was pointed out by the company rep. The cost of the total prototype board consisted of 30% component cost and 70% labor and setup fees, which seemed extravagant for such a simple design. Finally, the package arrived 8 days after it was shipped even though 3-day shipping was selected at the checkout. In summary, Macrofab is not the best custom PCB supplier and it is recommended that future purchases of this board be made through Oshpark (colleagues have had good experiences).

7.2 Reflections

This research project pushed me to reevaluate the way I approach design problems. In similar projects that I have completed through internships, I worked on finding a solution for 8 hours a day, 5 days a week until the problem was solved. There was little time to iterate on the process or learn sufficient background. This project allowed me the time to deliberately make design choices with all of the information needed to make the decision. I had the space to iterate on multiple version of my design and I enjoyed being able to see the progression of my work.

Another important skill I learned through this project is how to create my own custom PCB. I have used many components containing PCBs, but I never knew how easy it was to make your own as opposed to using a breadboard. Learning the KiCad software was time consuming and sometimes frustrating, but overall it was a valuable experience and I am confident that I can and will create more in the future.

Chapter 8: Conclusion

The final design of the sensor meets the design requirements laid out by the initial project proposal. The sensor body provides a more durable insulation to the pins and minimizes leaks through the coolant chamber as compared to the fiberglass insulation tape and brittle epoxy used in the phase 1 prototype. The low emissivity gold coating on the stainless-steel pin collects data that corresponds closely to the temperature range that was expected through the initial simulations. The method of gold coating is affordable and again provides durability and minimalizes variation in the sensor assembly process. The custom circuitry replaces the NI DAQ system used in phase 1 with a cost effective and user-friendly alternative, while still allowing room for further customization in the data collection between sensors. The coolant system is self-contained using a small 12V pump and a bucket of water, and the touchscreen added to the Raspberry Pi allows the user to ensure the test is running correctly every time. The sensor fits within the size and temperature durability constraints while meeting the low-cost requirement per unit.

Design is an iterative process, therefore the future work recommendations center around the fact that this sensor design should be revisited and revised as necessary. The SIMCenter plans on using the oven model provided by GE Appliances to create a detailed simulation and use this to test the 3D printing materials that GE Appliances has available to create the sensor body. This will determine the best possible material and enable full temperature testing using the sensor. This project will continue through phase 2 into next year where a new student researcher will begin work. The heat flux equations will be incorporated into the sensor's code so that it outputs heat flux values instead of temperature and a calibration method will be created. It is the intention that GE Appliances will begin using the sensors at this point and provide design feedback to enable the sensor to be optimized for everyday use. Eventually the heat flux data collected by this sensor will be used to create a theoretical model of the heat flux inside the oven environment, ultimately shortening the calibration and simulation phases of the oven design process.

References

[1] Sahu, Suraj Kant. “Model Supported Heat-Flux Sensor Development”. 2018. The Ohio State University, Master’s Thesis.

[2] “GEA Oven Proposal Phase 2”. 2019. The Ohio State University.

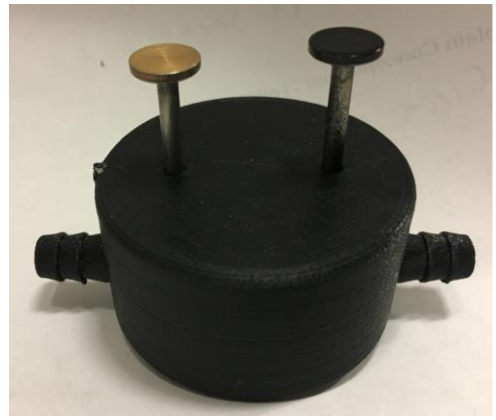
[3] “AD 595 Datasheet.” *Sparkfun.com*, 2017, www.sparkfun.com/datasheets/IC/AD595.pdf.

[4] Adafruit Industries. “Thermocouple Amplifier MAX31855 Breakout Board (MAX6675 Upgrade).” *Adafruit Industries Blog RSS*, www.adafruit.com/product/269.

[5] Image Sources: Duratec 1000 Machinable Ceramic, Duratec.com; Rescor 310M Fused Silica Foam, Rescor.com; Polypropylene at Film Grade, Indiamart.com; PEEK 450G 30% Glass Fill, plastock.co.uk; Thermax PEI 3D filament, 3Dxtech.com; Powder Materials for 3D Printing, 3Dprintingindustry.com

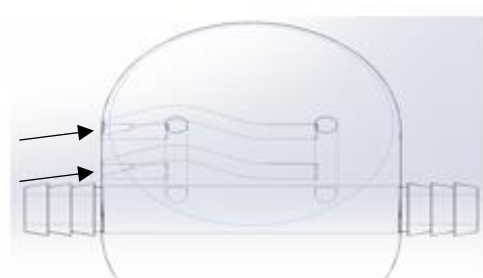
Appendix A: Assembly Instructions

1. Insert the high and low emissivity pins into the holes in the sensor body as shown.

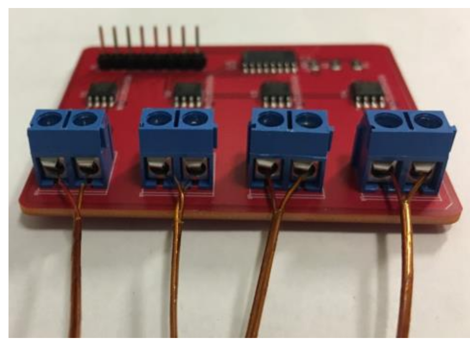


2. Use a rubber mallet or similar device to carefully push the pins into the sensor body until the bottom faces are flush with the sensor body's top surface. Take care to not harm the top coating of the pins.

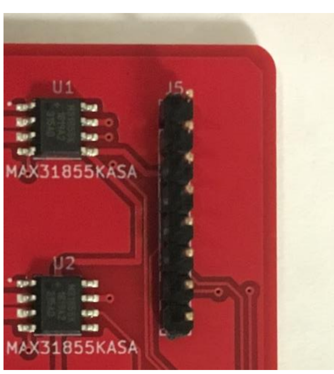
3. Insert the thermocouples into the sensor body using the channels shown. 2 thermocouples fit into each hole, one inserted straight into the hole with a depth of 0.5" and the other inserted slightly angled to the left with a depth of around 1.5".

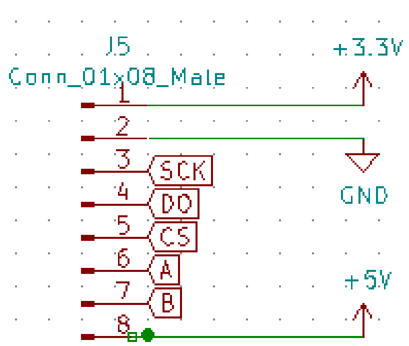


4. Attach the thermocouples to the PCB using the screw terminals. The red coated wire is negative (left terminal) and the yellow is positive (right terminal) for each pair. Ensure they are tight by lightly tugging on the thermocouple wire – they should not come loose at all.



5. Connect the Raspberry Pi to the PCB using female – female wires. The diagram below shows the pinout for the PCB and a Raspberry Pi pinout can be found in the packaging that the Raspberry Pi is shipped in.





SCK = pin 25

DO = pin 24

CS = pin 18

A = pin 9

B = pin 11

6. Connect the touchscreen HAT to the Raspberry Pi 5V and Ground. Screw the HAT to the Raspberry Pi for stability.
7. Connect 2.5A power supply and verify that Raspberry Pi powers up.
8. Cut plastic tubing to desired length to reach from either end of sensor to coolant reservoir outside of the oven. Attach outlet of pump to one end of the plastic tube (either end is fine). Power up pump and verify function.

Appendix B: Python Code

```
# Import necessary libraries
import time
import csv

import Adafruit_GPIO.SPI as SPI
import Adafruit_MAX31855.MAX31855 as MAX31855
import RPi.GPIO as GPIO

# Set up csv file to save data
csv = open('HFData.csv', "w")
csv.write('time (s), TC 1, TC 2, TC 3, TC 4\n')

# Define a function to convert celsius to fahrenheit.
def c_to_f(c):
        return c * 9.0 / 5.0 + 32.0

# Configure Raspberry Pi software SPI
CLK = 25
CS  = 24
DO  = 18
sensor = MAX31855.MAX31855(CLK, CS, DO)

# Configure CD4052B
GPIO.setmode(GPIO.BCM)
GPIO.setup(16,GPIO.OUT)
GPIO.setup(12,GPIO.OUT)

# Initialize time variable
t = 0

# Loop printing measurements every second.
print('Press Ctrl-C to quit.')
while True:

    # Save the time of measurement
    csv.write('{0:0.3F},'.format(t))
    t = t + 1

    # Read thermocouple #1
    GPIO.output(12, GPIO.LOW)
    GPIO.output(16, GPIO.LOW)

    temp = sensor.readTempC()
    internal = sensor.readInternalC()
    print('Thermocouple 1 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(temp, c_to_f(temp)))
    print('    Internal 1 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(internal, c_to_f(internal)))
    csv.write('{0:0.3F},'.format(c_to_f(temp)))
```

```
    time.sleep(1.0)

   # Read thermocouple #2
    GPIO.output(12, GPIO.LOW)
    GPIO.output(16, GPIO.HIGH)

    temp = sensor.readTempC()
    internal = sensor.readInternalC()
    print('Thermocouple 2 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(temp, c_to_f(temp)))
    print('    Internal 2 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(internal, c_to_f(internal)))
    csv.write('{0:0.3F},'.format(c_to_f(temp)))
    time.sleep(1.0)

   # Read thermocouple #3
    GPIO.output(12, GPIO.HIGH)
    GPIO.output(16, GPIO.LOW)

    temp = sensor.readTempC()
    internal = sensor.readInternalC()
    print('Thermocouple 3 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(temp, c_to_f(temp)))
    print('    Internal 3 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(internal, c_to_f(internal)))
    csv.write('{0:0.3F},'.format(c_to_f(temp)))
    time.sleep(1.0)

   # Read thermocouple #4
    GPIO.output(12, GPIO.HIGH)
    GPIO.output(16, GPIO.HIGH)

    temp = sensor.readTempC()
    internal = sensor.readInternalC()
    print('Thermocouple 4 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(temp, c_to_f(temp)))
    print('    Internal 4 Temperature: {0:0.3F}*C /
{1:0.3F}*F'.format(internal, c_to_f(internal)))
    csv.write('{0:0.3F}'.format(c_to_f(temp)) + '\n')
    time.sleep(1.0)
```